

# The modeling design integral the electrostatic microelectromechanical switch of capacitive type

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**Abstract.** This article presents the optimization and static modeling of the design an integral microelectromechanical switch of capacitive type based on a parametric 3D model using finite element analysis software complex ANSYS. The values of the pull-down voltage and switching time are determined. The obtained results give a good theoretical help in the development of various high-performance electrostatic microelectromechanical switches.

## 1 Introduction

Microelectromechanical systems (MEMS) have achieved tremendous success since their introduction in the 1960s in the form of resonant gate transistors. The development of MEMS technology has led to the emergence of two new classes of devices – sensors and actuators, which continue to replace their macro-scale counterparts due to their miniature size, low cost, low power consumption and possible integration with semiconductor integrated circuit (IC) technology. However, radio-frequency (RF) electronic equipment has always needed switches that make low losses in the open state and provide high isolation in the closed state, with high permissible signal power and low control power.

The first switch to fully meet the requirements of steel electromagnetic relays. After many years of improvement, modern RF electromagnetic relays provide low on signal loss and high isolation in the off state, but they have such disadvantages as large size, high cost and limited life (from hundreds of thousands to tens of millions). Switches on PIN-diodes and field-effect transistors (FET) based on GaAs have a number of advantages over electromagnetic relays, which are high speed operation, small size and weight, as well as low power control. But they are characterized by higher insertion losses and for this reason in a number of applications cannot replace electromechanical switches.

Further search for developers led to the development of RF switches based on MEMS technologies that combined some of the advantages of semiconductor and relay devices. The first reports of MEMS switches developed specifically for RF applications date back to the early 1990s [1-8]. Recently, several micromechanical switches have been manufactured using MEMS technologies.

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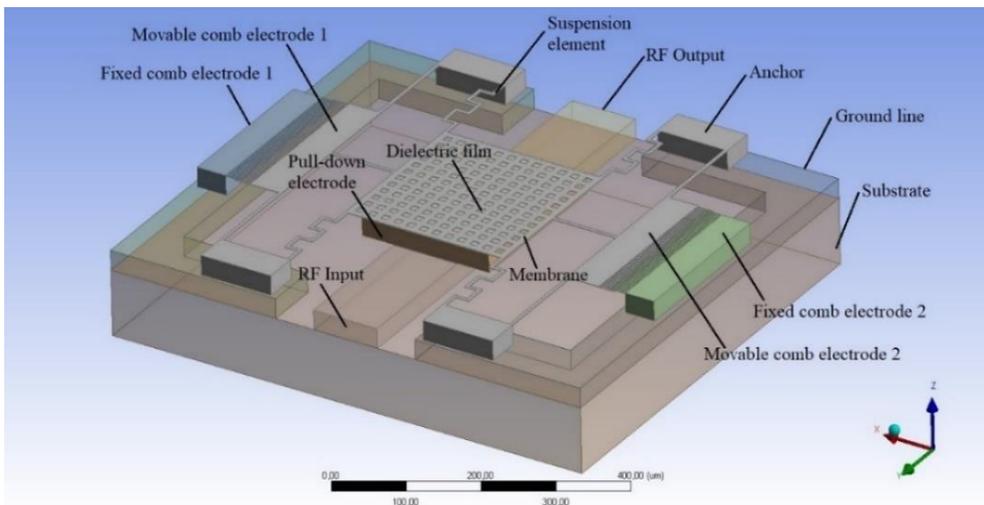
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The transition to micro-scale RF MEMS switches is reflected in the significant growth of the market of RF MEMS segment and their applications. Typical applications of RF MEMS switches are tele- and radio communications, industry, mobile devices, base stations, radars, antenna switches. According to the marketing research and analysis of technologies conducted by Yole Development Group, the average annual growth rate of profit of the RF segment of MEMS market is 10% per year: from 2,3 billion dollars in 2018 to 4,4 billion dollars in 2024, which exceeds the average annual growth rate of profit from such segments of MEMS market as: inertial sensors, pressure sensors, microphones and optical MEMS devices [9]. This expansion of the RF MEMS segment is due to the successful transition of these technological solutions from the research the commercial sector. In the commercial sector, these devices often experience uncertain and frequently changing environmental conditions that can significantly affect their performance and reliability.

In this article we carried out modeling and optimization of the developed design of the integral MEMS switch of capacitive type by means of methods of the finite element analysis in the ANSYS software complex.

## 2 Description of the design of a MEMS switch

MEMS switches can be classified into three main parameters: (1) the structure or type of inclusion in the RF electrical circuit – serial or parallel inclusion; (2) the type of design of the mechanical switching element – cantilever or cantilever and membrane; (3) the type of contact – resistive (metal-metal) and capacitive (metal-dielectric-metal). This article presents a study of the design of the membrane MEMS switch with capacitive contact type in the RF electrical circuit developed by the authors. The main elements of the switch design are shown in Fig. 1.



**Fig. 1.** Design and main elements of MEMS switch.

As shown in Fig. 1 the switch design uses a perforated metal membrane as the switching mechanism. The membrane is fixed to the anchor areas by means of elastic suspension elements with an air gap relative to the RF transmission line of the coplanar waveguide, as well as relative to the fixed pull-down electrode. A dielectric film is applied to the surface of the fixed pull-down electrode. Thus, the RF transmission line forms a

variable capacitance capacitor with the grounded membrane. At the same time, in the case of the down position of the membrane (in contact with the dielectric film of the membrane), the RF signal entering the input line is shunted to the grounding lines of the coplanar waveguide.

In addition, the design of the presented switch provides an electrostatic clamp, which is formed by two comb drives: (1) movable comb electrode 1 - fixed comb electrode 1; (2) movable comb electrode 2 - fixed comb electrode 2. This electrostatic clamp is designed to hold the membrane in its original position (in the case when the switch is open and the RF signal with low losses enters the RF output of the transmission line) when its structure is affected by linear accelerations, shock and vibration induced by shock pulses. This is because linear accelerations, mechanical shocks and vibrations are the three main environmental influences that can cause unwanted short circuits or open RF transmission lines. In turn, this will cause errors and malfunction of the entire RF device or the entire RF system into which the switch is integrated.

In addition to the influence of environmental factors to malfunction MEMS switch leads Brownian noise. Brownian noise leads to a random change in capacitance, which in turn leads to additional phase and amplitude noise at the RF output of the device. In this regard, the quality indicator  $Q$  of a well-designed device should lie within:  $0,3 \leq Q \leq 3$  so that the switching time is limited only by the mechanical parameters (mass, stiffness coefficient, etc.) of the switch design.

The quality index of MEMS structure is determined by the Equation (1):

$$Q = \left( \frac{k}{\omega_0 b} \right) \quad (1)$$

where  $k$  – the stiffness coefficient;  $\omega_0 = \sqrt{\frac{k}{m}}$  – the angular frequency;  $m$  – the mass of the structure;  $b$  – the damping coefficient.

The geometric parameters of the structural elements of the MEMS switch are given in Table 1.

**Table 1.** Geometric parameters of MEMS switch design elements

Structural element	Dimensions (length x width x thickness), $\mu\text{m}$
Membrane	250x250x1
Fixed pull-down electrode	245x200x10
Dielectric film	245x200x0,15
Suspension element (meander)	35x5x1
Anchor	110x50x30
Hole in membrane	10x10x1

The materials of the main structural elements of MEMS switch is aluminum [10], and as the dielectric material is used  $Si_3N_4$ .

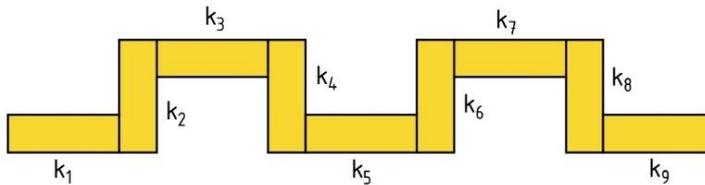
### 3 Theoretical basis

Since the MEMS switch designs have small deviations at the micro level, their mechanical behavior can be analyzed by knowing the stiffness constant of the elastic suspension elements  $k$  (N/m) [11]. In the design of the proposed switch elastic suspension elements have a serpentine shape.

Thus, the stiffness constant is calculated by determining the stiffness coefficient of individual elements, as shown in Fig. 2, followed by finding the effective stiffness coefficient  $k_{eff}$  [12]. The Equation (2) for determining the effective stiffness coefficient  $k$  has the form:

$$k = Ew \left( \frac{t}{l} \right)^3 \quad (2)$$

where  $E$  – Young's modulus;  $w$  – the width;  $t$  – the thickness;  $l$  – the length of the beam.



**Fig. 2.** An elastic suspension element having two square meanders grouped from individual elements with constant stiffness  $k$ .

Thus, the average value of the constant stiffness of the elastic element  $k_{eff}$ , shown in Fig. 2, defined by Equation (3):

$$\frac{1}{k_m} = \frac{1}{k_1} + \frac{1}{k_2} + \frac{1}{k_3} + \frac{1}{k_4} + \frac{1}{k_5} + \frac{1}{k_6} + \frac{1}{k_7} + \frac{1}{k_8} + \frac{1}{k_9} \quad (3)$$

The effective stiffness constant  $k_{eff}$  can be determined by Equation (4):

$$k_{eff} = 4k_m \quad (4)$$

MEMS switches are triggered when an electrostatic force is present between the fixed pull-down electrode and the membrane. This force causes the membrane to deflect and come into contact with the RF transmission line [11]. The magnitude of the pull-down voltage is determined by the Equation (5):

$$V_p = V \left( \frac{2}{3} \right) = g_0 = \sqrt{\frac{8kg_0^3}{27\varepsilon_0 Ww}} \quad (4)$$

where  $g_0$  – the air gap value;  $\varepsilon_0$  – the vacuum permittivity;  $W$  – the width of the membrane;  $w$  – the width of the fixed pull-down electrode.

The switching time  $t_s$  is used to determine the switching speed. This is the rate at which the design of the switching element – membrane passes from one state to another. The mechanical regenerative switching force is increased by the use of higher voltages [12]. The switching time depends on the magnitude of the pull-down voltage  $V_p$  and the supply voltage  $V_s = 1.4V_p$  and is approximately determined by the Equation (5):

$$t_s \approx \frac{3.67V_p}{V_s} \quad (5)$$

The capacitance ratio is one of the key parameters of capacitive MEMS switches and is defined as the ratio of the capacitance of the variable capacitor in the down position of the membrane and in the initial position, which are given by Equation (6) and Equation (7):

$$C_u = \frac{\epsilon_0 A}{g_0 + \frac{t_d}{\epsilon_r}} \quad (6)$$

$$C_d = \frac{\epsilon_0 \epsilon_r A}{t_d} \quad (7)$$

where  $t_d$  – the thickness of the dielectric film;  $\epsilon_r$  – the dielectric constant of the material.

In the initial position, the value of the air gap between the membrane and the dielectric film is maximum, and in the down position they are in contact with each other. The capacity ratio is given by the Equation (8):

$$C_r = \frac{C_d}{C_u} \quad (8)$$

Resistance MEMS switch consists of two variables  $R_{s1}$  and  $R_s$ , where  $R_{s1}$  due to the loss of RF signal transmission lines of the coplanar waveguide and is defined by Equation (9):

$$R_{s1} = 2\alpha Z_0 l \quad (9)$$

where  $\alpha$  – the RF signal losses in the transmission line of the coplanar waveguide expressed in Np/m.

The second component of  $R_s$  is determined by the resistance of the mobile electrode. If the thickness of the movable electrode is less than  $2\delta$ , where  $\delta$  the depth of the skin layer, the resistance of the switch is constant and does not change with the RF signal frequency. However, if the thickness of the movable electrode is greater than  $2\delta$ , the resistivity of the conductor depends on the frequency of the RF signal according to  $\sqrt{f}$  in practice, as a rule, the thickness of the movable electrode and the RF MEMS switch design elements are taken equal to  $3 - 4\delta$ . The depth of the skin layer is determined by the Equation (10):

$$\delta = \sqrt{\frac{2}{\omega \mu \sigma}} \quad (10)$$

where  $\omega = 2\pi f$  – the circular frequency of variable current;  $f$  – the resonant frequency;  $\mu = 4\pi \cdot 10^{-7}$  – the magnetic constant.

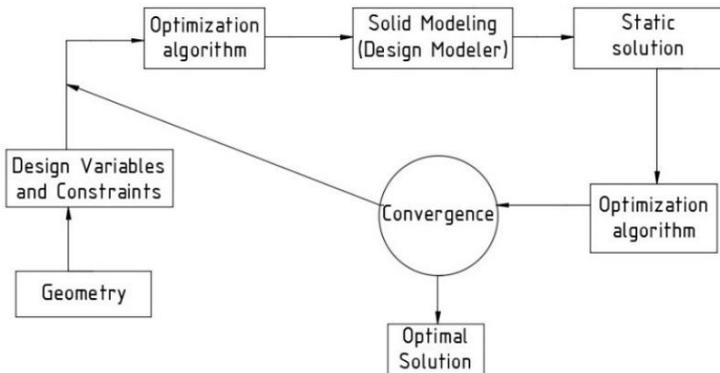
On the basis of the given theoretical data analytical modeling of the presented design of the presented capacitive MEMS switch is carried out [13].

## 4 Simulation of mechanical behavior of the device

The ANSYS program, based on finite element problem solving, provides two different methods for solving electrostatic-structural problems [14, 15]. This allows you to combine the results of modeling one area to solve related problems. In the case of an Electromechanical problem, the electrostatic and mechanical structural domains are solved

sequentially. The connection between the two regions is realized by the load vector, which is an electrostatic force acting on the boundary of the structural elements. In ANSYS, each domain is described by a database file called physics environment. In Electromechanical analysis, the interaction between the electrostatic medium and the structural medium is carried out by passing between two relevant databases. The electrostatic problem is based on the solution of the Laplace equation in various homogeneous domains. By solving this equation, it is possible to determine the potential distribution in the environment and on the surface of the conductors and thus calculate the electrostatic force between the two conductors. The next step is solved the structural problem in a structural environment. In fact, the deformed shape of the membrane under the action of electrostatic force is obtained in accordance with the theory of plates/shells [16-18]. The structural region is then switched back to the electrostatic medium, updating the electrostatic grid. The iterative process continues until convergence between the two environments is achieved. The second method of realization of electrostatic-structural problem in ANSYS environment is the method of concentrated or induced order. This method is usually strongly coupled and is considered the fastest in terms of convergence time [19, 20]. It can be implemented using concentrated transducer elements, eliminating the disadvantage of a sequential process. Transducer elements store electrostatic energy and convert it into mechanical energy and conversely. The input data for the transducer elements are the voltage supplied to the opposite nodes, the maximum and minimum air gap. The displacement-capacitance ratio can be obtained from the solution of the electrostatic field problem. Compared to the sequential 3D connection method, electrostatic elements representing the environment (air between two conductors) are replaced by a set of transducer elements. In this way, a simulation of the coupled electrostatic structure can be performed.

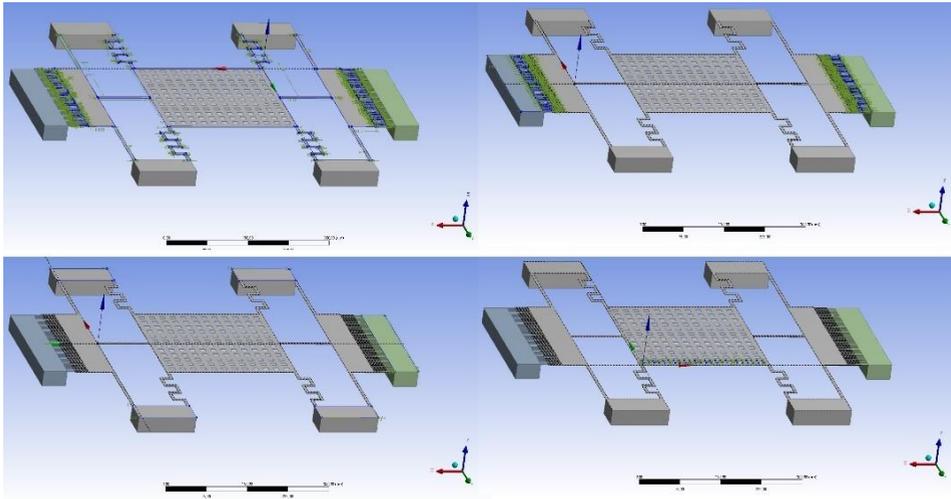
In addition, using the second method of solving problems in the ANSYS software package, MEMS switch optimization for specific output parameters can be carried out, as shown in Fig. 3.



**Fig. 3.** Traditional approach to MEMS device optimization.

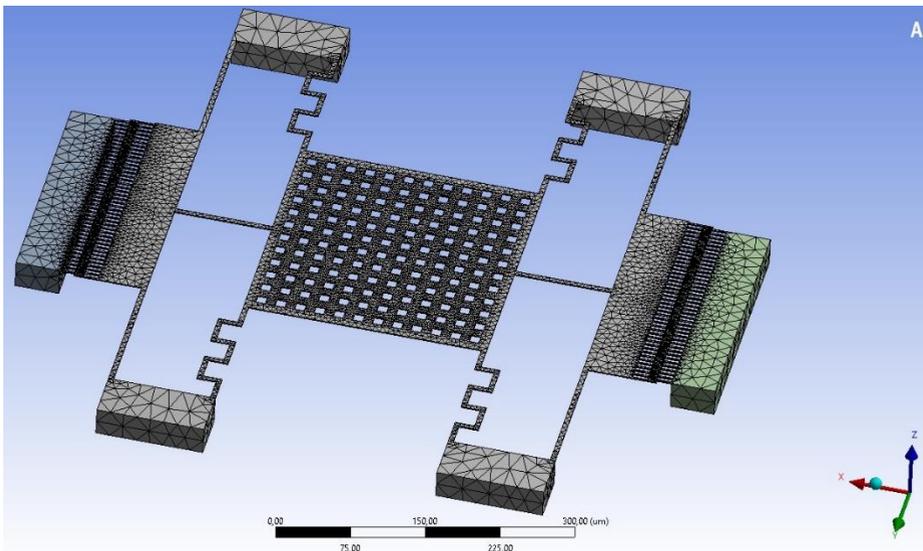
For finite element analysis, the first step is to develop a parametric model of the 3D model of the MEMS switch, which allows you to describe the design of the device using a different set of dimensional characteristics that determine the geometry of the object, the relationship conditions and the relationship of individual elements together.

The parametric 3D model of the switch developed by MEMS is shown in Fig. 4. Parametric 3D model allows you to quickly change one or more dimensions of the structure, which significantly reduces the time for calculations. Each build element is assigned its own unique parameter name, and then the parameter is assigned a numeric value. If you change the value of this parameter, the 3D model of the switch is automatically recalculated.



**Fig. 4.** Parametric 3D model of MEMS switch.

The second important step in numerical simulation of continuum mechanics problems is the quality of the computational finite element mesh. The question of mesh quality is of critical importance in contact problems, since, on the one hand, small elements with higher accuracy reflect the behavior of the structure when loads are applied to it, and on the other hand, such problems, due to their nonlinearity, require significant computational resources. A fragment of a finite element grid with a given characteristic cell size of  $15\ \mu\text{m}$  is shown in Fig. 5.

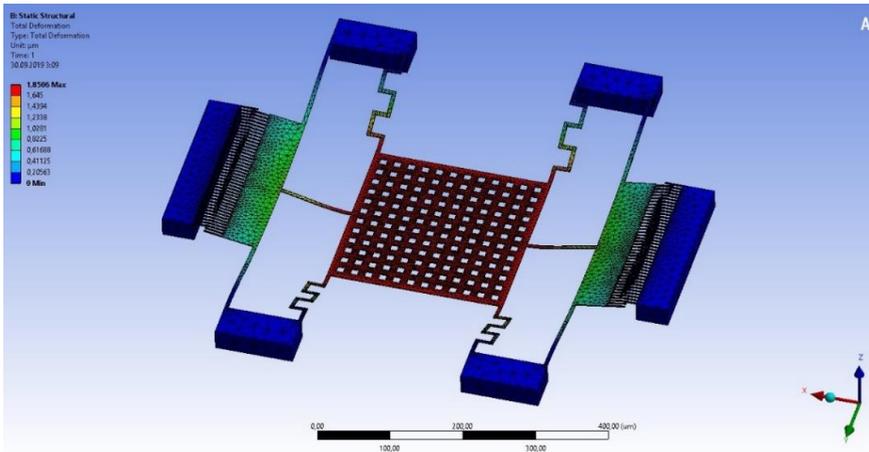


**Fig. 5.** Finite element meshes parametric 3D model MEMS switch.

When solving a static strength problem in the Static Structural analysis module, displacements, stresses and strains due to applied loads are determined. It is assumed that the effects associated with inertia and damping are small. In Static Structural analysis calculations, user-defined loads are applied incrementally: the solution is broken down into steps. In the first step, displacements and stresses are calculated when a load is applied to the source system that is approximately equal to the partial of the user-defined load divided

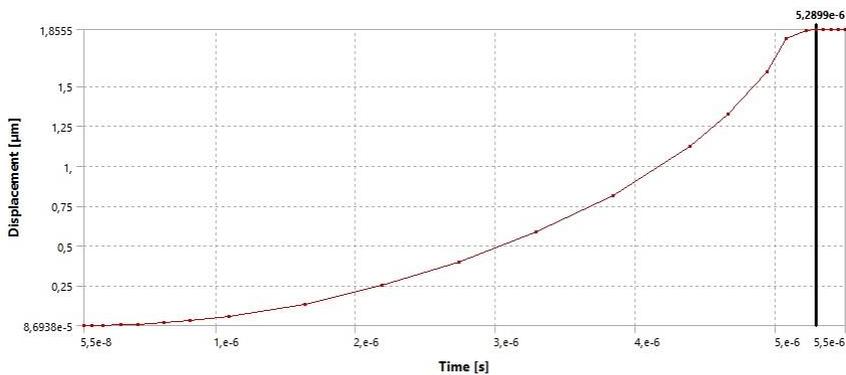
by the number of steps. In the next step, the load is applied to the deformed system, the state of which was determined in the previous step, and so on.

The most acceptable from the point of view of the accuracy of the result and the cost of machine time should be considered a computational experiment performed on a grid with a characteristic cell size of 15  $\mu\text{m}$ . Fig. 6 illustrates the deformation of the actuator – membrane MEMS switch in the down position.



**Fig. 6.** Deformation of the MEMS switch membrane when an electrostatic field is applied.

For Fig. 7 the dependence of the MEMS switch membrane displacement on time is shown. In this case, the time of switching the membrane to the down position is 5.29  $\mu\text{s}$  with the magnitude of the pull-down voltage of 15 V.



**Fig. 7.** The dependence of the MEMS membrane displacement of the switch on time.

## 5 Conclusion

In this article, using the ANSYS software package, a parametric 3D model of the capacitive MEMS switch is developed. The optimization of the design using the built-in modules optimization of the design in the ANSYS software package, as well as static finite element modeling using numerical methods to estimate the value of the control voltage and switching time. According to the results of static modeling, the required pull-down voltage for the presented switch design with one central fixed pull-down electrode is 15 V and the switching time to the down position is 5.29  $\mu\text{s}$ . The theoretical data presented in this article are the basis for the design of electrostatic MEMS switches.

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